FECAL COLIFORM TRANSPORT AS AFFECTED BY SURFACE CONDITION

R. M. Roodsari, D. R. Shelton, A. Shirmohammadi,
Y. A. Pachepsky, A. M. Sadeghi, J. L. Starr

ABSTRACT. *Land application of manure is recommended to recycle organic matter and nutrients, thus enhancing the soil quality and crop productivity. However, pathogens in manure may pose a human health risk if they reach potable or recreational water resources. The objective of this study was to observe and quantify the effects of vegetated filter strips (VFS) on surface and vertical transport of fecal coliform (FC) bacteria, surrogates for bacterial pathogens, released from surface-applied bovine manure. A two-sided lysimeter with 20% slope on both sides was constructed with a sandy loam soil on one side and a clay loam soil on the other. Each side of the lysimeter was divided into two subplots (6.0 × 6.4 m), one with grass and the other with bare soil. Plots were instrumented to collect runoff samples along a 6.0 m slope at three equidistant transects. Samples of runoff were also collected in a gutter at the edge of each plot. All plots were equipped with multi-sensor capacitance moisture probes to monitor water content through the soil profile. Bovine manure was applied at the top of each plot in a 30 cm strip. Rainfall was simulated at a 61 mm h^{-1} intensity using a portable rainfall simulator. Surface runoff rate was measured and water quality sampled periodically throughout the simulation. Soil samples were taken at incremental depths (0-60 cm) after each simulation. Runoff (as % of total rainfall) decreased from 93% to 12% in the bare vs. vegetated clay loam plots and from 61% to 2% in the bare vs. vegetated sandy loam plots. The reduced runoff from vegetated plots decreased the surface transport of FC while increasing its vertical transport. The amount of FC in runoff (as % of applied) decreased from 68% to 1% in the bare vs. vegetated clay loam plots and from 23% to non-detectable levels in the bare vs. vegetated sandy loam plots. These data indicate that VFS can reduce surface transport of FC, even for slopes as high as 20%, especially in soils with high infiltration (e.g., sandy loam).*

Keywords. *Fecal coliform, Infiltration, Overland flow, Transport.*

Deterioration of water quality associated with non-point-source (NPS) pollution has recently become a great concern. A review of available information indicates that agriculture is one of the major contributors of NPS pollution to both surface water and groundwater (USEPA, 1994). In particular, manure associated with concentrated animal agriculture is a major source of microbial pollution, including various pathogenic microorganisms (USDA and EPA, 1999). Recent outbreaks attributed to manure-borne *Escherichia coli* O157:H7 in Walkerton, Ontario (Health Canada, 2000) and *Cryptosporidium parvum* (*C. parvum*) in Milwaukee, Wisconsin (Hoxie et al., 1997), resulting in numerous illnesses and several deaths, illustrate the necessity of mitigating microbial pollution.

Cattle, swine, and poultry manure provide valuable organic material and nutrients for crops and pasture. Land application of manure is recommended to recycle nutrients and organic matter to enhance soil quality and crop productivity (USDA and EPA, 1999). However, excessive application of animal manure may pose a public health threat if pathogens are transported to potable and recreational waters. Previous studies have documented contamination of surface water sources with *C. parvum* (Hansen and Ongerth, 1991; Ong et al., 1996) and *E. coli* O157:H7 (Johnson et al., 2003) associated with intensive dairy or beef cattle operations.

One of the promising management practices for controlling microbial contamination is directing the flow of contaminants through a vegetated filter strip (VFS). Previous research demonstrates that VFS can efficiently reduce the overland flow of sediment (Kao and Barfield, 1978; Li and Shen, 1973; Wilson, 1967) and nutrients (Bingham et al., 1980; Chaubey et al., 1994; Haggard et al., 2002). The mechanisms of sediment and nutrient removal by VFS are filtration, adsorption to soil and plant surfaces, and absorption by plant roots (Fajardo et al., 2001). Despite the relevance of these studies to microorganisms, the mechanisms of removal may differ because of different physical properties; microorganisms are similar in size to silt or coarse clay particles but with densities similar to water.

Article was submitted for review in October 2004; approved for publication by the Soil & Water Division of ASAE in May 2005.

Trade names are used to provide specific information. Mention of a trade name does not constitute a guarantee of the product by USDA or endorsement over similar products.

The authors are **Reza M. Roodsari,** Risk Assessment Fellow, USDA-FSIS; **Daniel R. Shelton,** Microbiologist, USDA-ARS Environmental Microbial Safety Laboratory, Beltsville, Maryland; **Adel Shirmohammadi, ASAE Member Engineer,** Professor, Department of Biological Resources Engineering, University of Maryland, College Park, Maryland; **Yakov A. Pachepsky,** Soil Scientist, **Ali M. Sadeghi, ASAE Member Engineer,** Soil Physicist, and **James L. Starr,** Soil Physicist, USDA-ARS Environmental Quality Laboratory, Beltsville, Maryland. **Corresponding author:** Reza Roodsari, USDA-FSIS, Office of Public Health Science, 1400 Independence Avenue, SW Room 382, Aerospace Building, Washington, DC 20250-3700; fax: 202-690-6337; e-mail: reza.roodsari@fsis.usda.gov.

Although the majority of studies support the ability of VFS to remove microorganisms from overland flow, the reported efficacies are highly variable (Coyne et al., 1995; Crane et al., 1983; Dickey and Vanderholm, 1981; Gillfillen, 1994; Hunt et al., 1979; Srivastava et al., 1996; Young et al., 1980). For example, Lim et al. (1997) reported that all FCs were removed within the first 6.1 m of a VFS used to treat runoff from a pasture with applied manure, while Schellinger and Clausen (1992) reported only a 30% decrease in bacterial concentrations from a dairy manure detention pond after transport through a VFS. These studies suggest that critical factors controlling microbial surface transport are not sufficiently understood, resulting in substantial disparity in current VFS design recommendations (Moore et al., 1988; Walker et al., 1990; NRCS, 1997).

The objective of this study was to observe and quantify the effect of VFS in reducing the loss of FC released from surface-applied bovine manure through surface runoff and infiltration. Results of this study are intended to assist in developing design criteria for VFS by elucidating the predominant mechanisms responsible for mitigation of microbial surface transport.

Materials and Method

The experimental site was located at the Patuxent Wildlife Research Refuge (U.S. Department of Interior) at Beltsville, Maryland. A two-sided lysimeter (12.7 m wide by 21.5 m long) with 20% slope on both sides was instrumented to monitor the surface and vertical water flow and transport of FC (fig. 1). The bottom and walls of the lysimeter were lined with heavy-gauge plastic to prevent loss of contaminants. The average depth of the lysimeter was approximately 3 m.

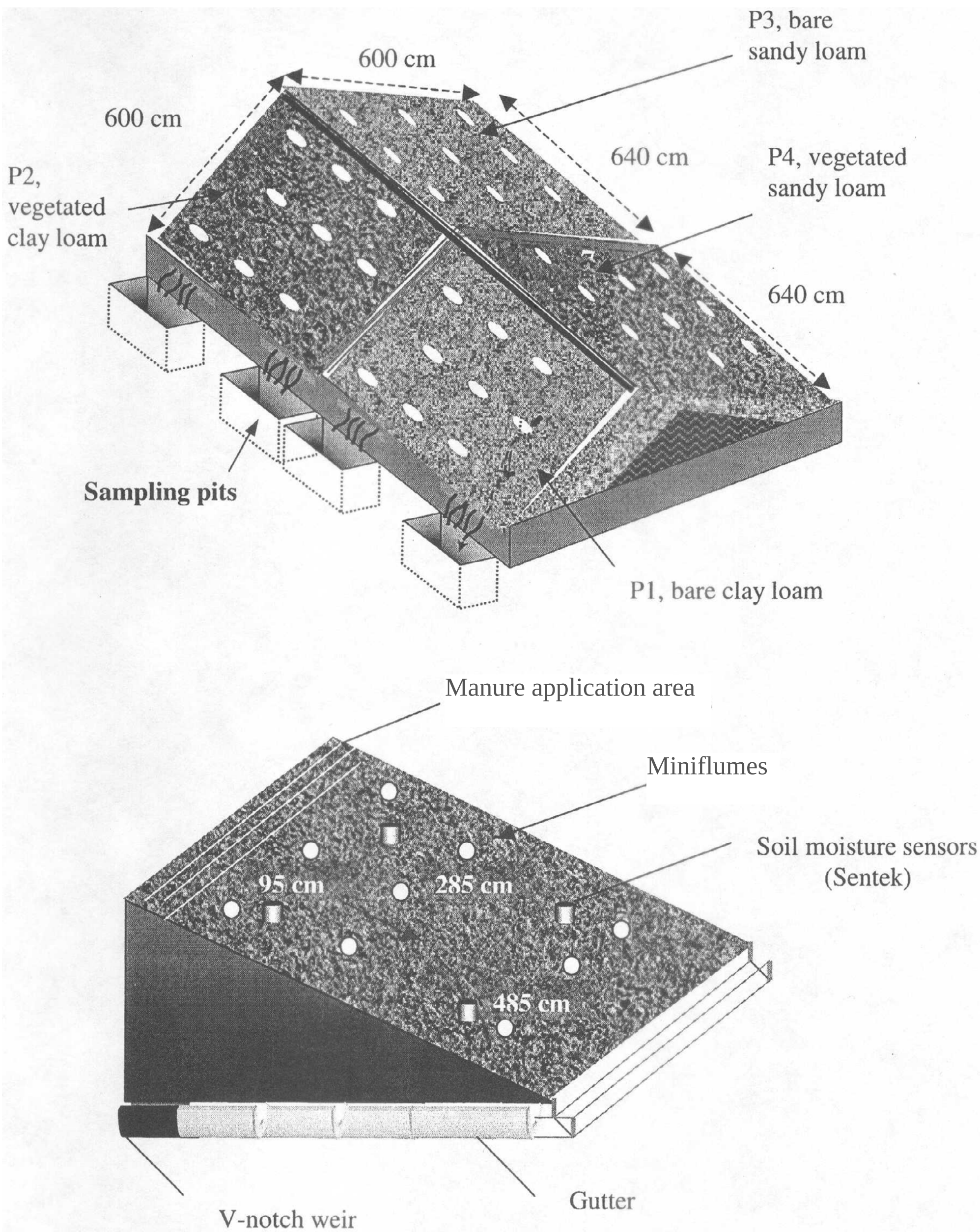

Figure 1. Schematic diagram of lysimeter.

The topsoil was sandy loam on one side of the lysimeter and clay loam on the other side. Both sides had a gravel layer below the 60 cm soil depth. The organic matter content and pH of the top 10 cm of the soil profile were measured to be 2.7% ±0.9% and 5.9 ±0.6, respectively, for the clay loam and 1.7% ±0.9% and 6.2 ±0.3, respectively, for the sandy loam. Each side was divided into two plots to simulate bare and vegetated (orchard and fescue grass) surface conditions. The lysimeter was equipped with a gutter to collect surface runoff at the edge of each plot. A V-notch weir was installed at the end of the gutter to measure total surface runoff and to develop flow hydrographs during rainfall simulation. Nine mini-flumes were installed within each plot to measure temporal and spatial distribution of FC in runoff. Three sets of three mini-flumes were placed 95, 285, and 490 cm from the line of the manure application area, and the gutter was located at the edge of each plot, 600 cm from the line of the manure application area. The mini-flumes were connected to sampling funnels outside the lysimeter via food-grade Tygon tubing buried about 20 cm depth below the soil surface. Four capacitance-based soil moisture sensors (Sentek) were installed in each plot to measure volumetric water contents within 5-15, 15-25, 25-35, and 35-45 cm depth intervals with 2 min frequency. A four-nozzle rainfall simulator was calibrated at the site to maintain a uniformity coefficient of approximately 90% for a rainfall intensity of 61 mm h^{-1}, corresponding to a 10 year (return period), 1 h (duration) storm in Maryland.

Experimental Procedures

The evening prior to each rainfall simulation, 20 kg of bovine manure was uniformly applied to a 30 cm wide strip at the top of each plot. The concentration or population of FC in the manure was determined prior to the initiation of each rainfall simulation. The initial FC population in the manure was 3.7×10^5, 5.5×10^5, 27.9×10^5, and 16.1×10^5 CFU per gram of manure on the bare clay loam, vegetated clay loam, bare sandy loam, and vegetated sandy loam, respectively. Differences in FC populations were due to manure inconsistencies that exist as a result of animal feeding diets.

Rainfall simulation events on bare plots were terminated after 55 min to simulate the desired 10 year, 1 h storm and because manure dissolution appeared to be complete. Simulations on vegetated plots were extended for a longer period in order to collect runoff in the gutter and mini-flumes for at least 1 h. Runoff from the mini-flumes and the gutter was measured continuously, and water quality samples were collected at 5 min intervals during simulations.

After the simulations, water samples from the mini-flumes were thoroughly mixed, and 50 mL subsamples were taken immediately to the laboratory for FC analysis. On the following day, soil samples were taken with a 2.54 cm ID core sampler from the areas adjacent to the mini-flumes and in the manure application areas at incremental depths down to 60 cm. The remaining manure residue was collected from the application area in bare plots to determine the remaining FC population.

The concentrations of FC in manure, runoff, and soil were determined using standard culture techniques. Ten grams of manure were diluted 1:10 with distilled water, dispersed for 2 min in a high-speed blender, and then again diluted 1:10 with distilled water. Runoff samples were centrifuged at 100 g in 12 mL conic tubes for 10 min to remove sediment. Soil samples were diluted 1:10 with distilled water, dispersed for 2 min in a high-speed blender, and then centrifuged as described above to remove soil particles. Two replicated 50 μL subsamples of the manure, runoff, or soil supernatants were placed onto MacConkey agar using a Spiral BioTech autoplater. Plates were incubated at 44.5°C for 18 h. A Synoptics limited protocol colony counter was used to count FC in CFU on each plate. All data are expressed as CFU per gram.

The standard error of the fraction of FC in runoff (s_f) was computed as:

$$s_f = f\sqrt{\frac{(s_Q)^2}{Q} + \frac{(s_{p-r})^2}{p-r}} = f\sqrt{Q\left(\frac{s_a}{a}\right)^2 + \frac{(s_p)^2 + (s_r)^2}{p-r}} \quad (1)$$

where

f = fraction of FC in runoff, $Q/(p-r)$
p = average count of FC before the simulation
r = average count of FC remaining at the surface of the application area
q = average count of FC in runoff
Q = average adjusted count of bacteria ($Q = q/a$)
a = average extraction efficiency
s = standard error of the values shown in subscripts.

Results and Discussion

The hydrographs (fig. 2) indicate that in the bare clay loam and bare sandy loam plots, runoff was initiated within 5 min of the initiation of a rain event. On the bare sandy loam plot, runoff remained approximately constant during the simulation. On the bare clay loam plot, runoff gradually increased during the simulation, probably due to surface sealing and reduction in infiltration. Much less runoff was observed in the vegetated plots. Runoff was not observed in either the vegetated clay loam or vegetated sandy loam plots until 40 min after the initiation of a rain event. Very little runoff was observed in the vegetated sandy loam plot even after 155 min of simulated rainfall (fig. 2).

Relative concentrations of FC in runoff (C/C_0, where C is the FC concentration in runoff samples and C_0 is the initial concentration of FC in the manure) decreased with time at various distances from the source of manure application on the bare clay loam and bare sandy loam plots (fig. 3). The regression equations relating $\log C/C_0$ (relative concentrations) versus time indicate this trend for all plots, especially for bare plots, regardless of soil texture (table 1). The decrease in FC concentrations with time reflects primarily the kinetics of FC release from manure. These values are higher than the manure dissolution rates of 0.003 to 0.008 min^{-1} reported in the literature (Bradford and Schijven, 2002; Shelton et al., 2003) for experiments in which infiltration but not runoff was allowed to occur. The higher rate of manure dissolution with runoff, as compared to infiltration, has also been previously documented by Moore et al. (1988).

In general, maximum FC concentrations in runoff decreased with the distance from the source of manure application because of dilution (fig. 3). However, substantial

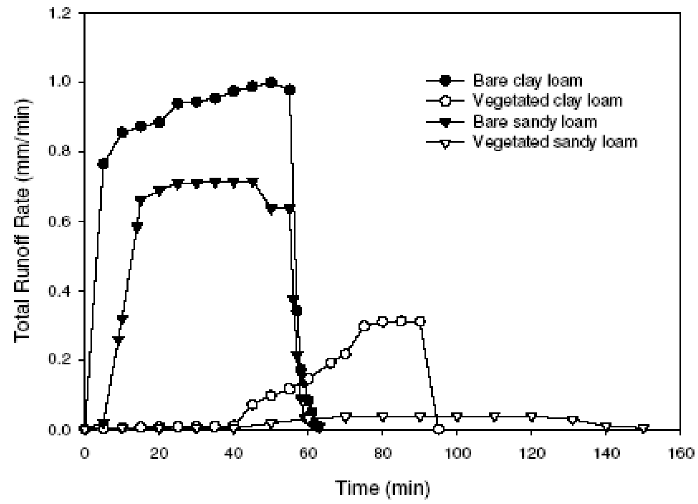

Figure 2. Runoff hydrographs for bare and vegetated clay loam and bare and vegetated sandy loam plots.

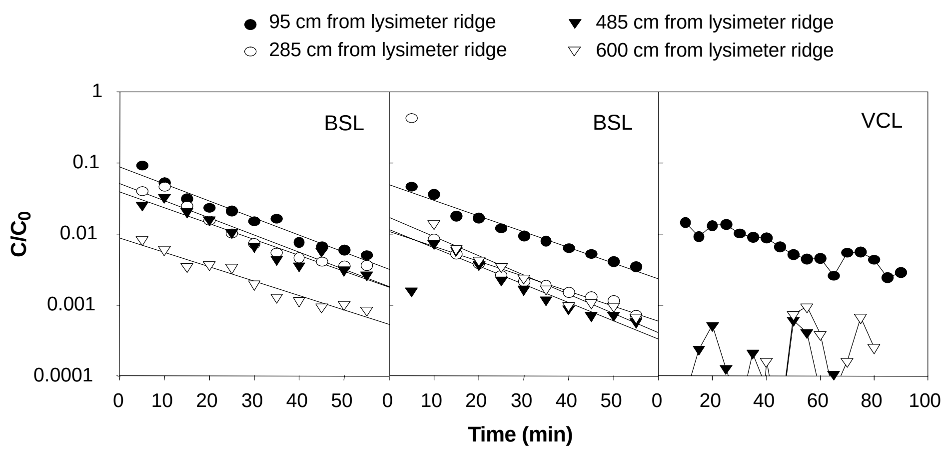

Figure 3. Relative concentrations of FC in runoff: BCL = bare clay loam, BSL = bare sandy loam, and VCL = vegetated clay loam. Data for vegetated sandy loam are not shown because FC was not detected in runoff.

variability was observed in FC concentrations at individual mini-flumes due to heterogeneity in surface flow paths. This variability was largely responsible for the lack of a consistent inverse correlation between FC concentrations and distance from the manure source. In vegetated plots, the exponential decrease in FC concentration values (C/C_0) was observed only in the clay loam plot at 95 cm from the source (fig. 3); this is similar to what was observed by Fleming et al. (1990). The concentrations of FC (C/C_0) at distances farther from the source were highly variable, indicative of spatial variability in infiltration and dilution. These data suggest that runoff was generated within the top 1 to 2 m strip of the vegetated clay loam plot, but the high infiltration capacity of the vegetated soil allowed this runoff to infiltrate (fig. 3). Such discontinuity of runoff at small scales was documented by Fiedler et al. (2002) and was attributed to differences in soil infiltration capacity and micro-topography.

Table 1. Regression equations of the dependence of relative FC concentrations in runoff C/C_0 on time *t*.

Plot	Distance (cm)	Equation, $\log(C/C_0)$	R^2
Bare clay loam	95	$0.943 - 0.024t$	0.96
	285	$0.712 - 0.024t$	0.93
	485	$0.598 - 0.022t$	0.92
	600	$0.051 - 0.020t$	0.94
Vegetated clay loam	95	$0.235 - 0.009t$	0.80
Bare sandy loam	95	$0.689 - 0.022t$	0.97
	285	$0.033 - 0.021t$	0.96
	485	$0.068 - 0.026t$	0.96
	600	$0.235 - 0.027t$	0.95

Surface transport of FC was substantially affected by vegetation. The concentration of FC was comparable at the 95 cm distance in the vegetated and bare clay loam plots; however, FC concentrations were dramatically lower in the vegetated clay loam plot than in the bare clay loam plot at farther distances from the source (fig. 4). Only three data points are shown for the 600 cm distance because no runoff was observed at the gutter in the vegetated clay loam plot until 40 min after the initiation of a rain event (fig. 4). Comparisons with the vegetated sandy loam plot are not shown because no FC was detected in runoff at any distance in these plots.

The concentrations of FC in the soil decreased with depth (fig. 5). The extent and depth of FC leaching was a function of both vegetation and soil texture. No FC were detected below the 1 cm depth in the bare clay loam plot, while they were detected up to the 20 cm depth at all distances from the source in the bare sandy loam plot. In general, FC concentra−

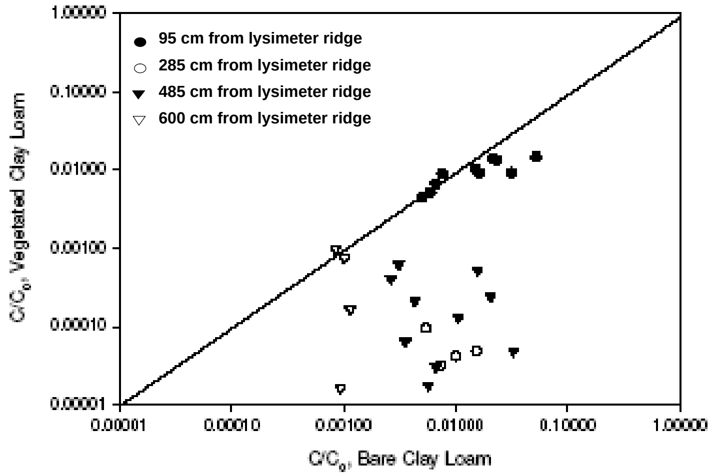

Figure 4. Comparison of FC ratios in runoff on vegetated clay loam vs. bare clay loam plot.

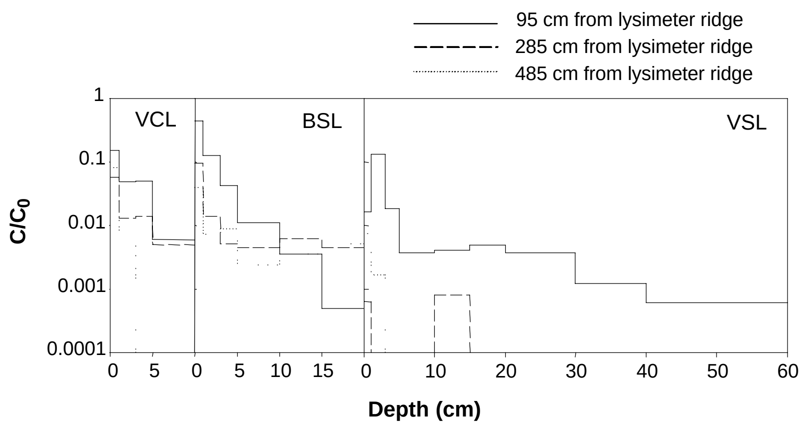

Figure 5. FC concentration ratios in soil: VCL = vegetated clay loam, BSL = bare sandy loam, and VSL = vegetated sandy loam. Data for bare clay loam are not shown because fecal coliform was not detected below the top cm layer.

tions in the top 1 cm of soil in the bare clay loam plot were close to the maximum concentration of FC observed in runoff. In the bare sandy loam plot, FC distributions in the soil were similar at the 285 and 485 cm distances. This corresponds to the similarity of FC concentrations in runoff at these distances (fig. 3). In the vegetated clay loam plot, FC were detected up to 10 cm below the soil surface (95 and 285 cm from the source), while in the vegetated sandy loam plot, FC were detected up to 60 cm below the soil surface at 95 cm from the source. The absence of FC at distances farther from the source in the sandy loam plot is the result of very low runoff due to high infiltration. Data indicate that vegetation enhances infiltration regardless of soil texture, thus promoting transport of FC into the soil profile in both the clay loam and sandy loam plots. It should also be noted that possible higher adsorption surfaces for FC in clay loam soil particles than in sandy loam soil may be the reason for the movement of FC to deeper depths in the sandy loam plots (e.g., 60 cm) than in the clay loam plots (e.g., 10 cm).

The mass balance for water and FC are shown in tables 2 and 3. Both vegetation and soil texture affected water balance. Runoff (as % of applied rainfall) decreased from 93% to 12% in the bare vs. vegetated clay loam plots and from 61% to 2% in the bare vs. vegetated sandy loam plots (table 2). The FC recovered (as % of applied) in runoff, in the soil profile, and in the residual manure solids were 68%, 5%, and 44% of the initial FC population, respectively, for the bare clay loam plot vs. 23%, 33% and 8%, respectively, for the bare sandy loam plot (table 3). Of the FC released from

Table 2. Runoff and infiltration (mm) in rainfall simulation experiments.[a]

	Clay Loam Soil		Sandy Loam Soil	
	Bare Plot	Vegetated Plot	Bare Plot	Vegetated Plot
Rainfall	56	92	56	127
Runoff	52 (93%)	11 (12%)	34 (61%)	3 (2%)
Infiltration	4 (7%)	81 (88%)	22 (39%)	124 (98%)

[a] Values in parentheses indicate percent of total rainfall.

Table 3. Bacteria mass (10^9 CFU) distribution in rainfall simulation experiments.[a]

	Clay Loam Soil		Sandy Loam Soil	
	Bare Plot	Vegetated Plot	Bare Plot	Vegetated Plot
Applied manure	7.5	11.0	56.0	32.3
Residual manure	3.3 (44%)	NM	4.4 (8%)	NM
Runoff	5.1 (68%)	0.1 (1%)	12.8 (23%)	ND (0%)
Soil	0.4 (5%)	9.9 (90%)	18.6 (33%)	3.6 (11%)

[a] Values in parentheses indicate bacteria recovered as a percentage of the total bacteria population in the applied manure.
NM = not measurable; ND = not detected.

the manure, essentially 100% was recovered from the bare clay loam plot, while 25% was recovered from the sandy loam plot.

The amounts of FC recovered in runoff and in the soil profile for the vegetated clay loam soil were 1% and 90%, respectively, vs. 0% and 11 %, for the vegetated sandy loam soil, respectively (table 3). The FC in the residual manure solids could not be determined in the vegetated plots because manure solids could not be collected from these plots. Assuming comparable FC release rates from manure for the bare and vegetated plots, the vast majority of FC infiltrated into the soil profile in the vegetated plots prior to the initiation of runoff (e.g., during first 40 min of simulation). Low soil recoveries of FC in the vegetated sandy loam suggest that FC leached below the sampling depth (60 cm). It should also be noted that the standard errors computed for the fraction of FC in runoff are higher for the bare plots than for the vegetated plots regardless of the soil type. This may be due to both higher runoff volume and its uneven and more channelized spatial transport in bare plots than in vegetated plots.

These data clearly demonstrate the role of vegetation and soil texture in controlling overland transport processes. They suggest that infiltration is the predominant mechanism responsible for attenuation of microbial surface transport. They also suggest that the variability in VFS efficacy observed in previous studies may be due to variability in infiltration rates (i.e., Coyne et al., 1995; Moore et al., 1988; Baxter-Potter and Gilliland, 1988; Kress and Gifford, 1984; Moore et al., 1983; Young et al., 1980). Consequently, the efficiency of a particular VFS can be properly evaluated only when factors affecting infiltration rates are taken into account.

Conclusions

The results of this study show that vegetation substantially attenuated the surface flow of water as compared to bare plots. Runoff was decreased from 93% to 12% in the bare vs. vegetated clay loam plots, and from 61% to 2% in the bare vs. vegetated sandy loam plots. The reduced runoff in the vegetated plots decreased the surface transport of FC while increasing their vertical transport. The amount of FC in runoff decreased from 68% to 1% in the bare vs. vegetated clay loam plots and from 23% to non-detectable levels in the bare vs. vegetated sandy loam plots. Therefore, enhanced infiltration may be the primary transport mechanism responsible for controlling runoff of FC from bovine manure.

This study illustrated the potential for VFS to reduce the runoff of microbial contaminants to surface water. Vegetation exerted a stronger influence than soil type, although both factors were important in minimizing runoff of manure-borne FC by affecting infiltration and vertical transport. The presence of vegetation promoted vertical FC transport close to the source of manure application but had a diminishing effect at increasing distances from the source, which may be attributed to initiation of concentrated flow.

Consequently, design parameters for VFS should account for those factors that control vertical transport, with the goal of optimizing infiltration rates. Results from this study also indicate that implementation of a VFS (about 3 to 4 m in width) at the edge of near-stream fields receiving animal manure may decrease or eliminate the transport of FC bacteria into the water system under well-maintained conditions (such as no concentrated flow).

References

Baxter-Potter, W. R., and M. W. Gilliland. 1988. Bacterial pollution in runoff from agricultural lands. *J. Environ. Qual.* 17(1): 27-34.

Bingham, S. C., P. W. Westerman, and M. R. Overcash. 1980. Effect of grass buffer zone length in reducing pollution from land application areas. *Trans. ASAE* 23(2): 330-336, 342.

Bradford, S. A., and J. Schijven. 2002. Release of *Cryptosporidium* and *Giardia* from dairy calf manure: Impact of solution salinity. *Environ. Sci. Tech.* 36(18): 3916-3923.

Chaubey, I., D. R. Edwards, T. C. Daniel, P. A. Moore Jr., and D. J. Nichols. 1994. Effectiveness of vegetative filter strips in retaining surface-applied swine manure constituents. *Trans. ASAE* 37(3): 845-850.

Coyne, M. S., R. A. Gilfillen, R. W. Rhodes, and R. L. Blevins. 1995. Soil and fecal coliforms trapping by grass filter strips during simulated rain. *J. Soil and Water Conserv.* 50(4): 405-408.

Crane, S. R., J. A. Moore, M. E. Grismer, and J. R. Miner. 1983. Bacterial pollution from agricultural sources: A review. *Trans. ASAE* 26(3): 858-866.

Dickey, E. C., and D. H. Vanderholm. 1981. Vegetative filter treatment of livestock feedlot runoff. *J. Environ. Qual*. 10(3): 279-284.

Fajardo, J. J., J. W. Bauder, and S. D. Cash. 2001. Managing nitrate and bacteria in runoff from livestock confinement areas with vegetated filter strips. *J. Soil and Water Conserv.* 56(3): 185-191.

Fiedler, F. R., G. W. Frasier, A. Jorge, J. A. Ramirez, and L. R. Ahuja. 2002. Hydrologic response of grasslands: Effects of grazing, interactive infiltration, and scale. *J. Hydrologic Eng*. 7(4): 293-301.

Fleming, R. J., D. M. Dean, and M. E. Foran. 1990. Effect of manure spreading on tile drainage water quality. In *Proc. 6th Int'l Symp.: Agricultural and Food Processing Wastes*, 385-392. St. Joseph, Mich.: ASAE.

Gillfillen, R. A. 1994. Fecal bacteria trapping in two lengths of grass filter strip. MS thesis. Lexington, Ky.: University of Kentucky.

Haggard, B. E., P. A. Moore, P. B. Delaune, D. R. Smith, S. Formica, P. J. Kleinman, and T. C. Daniel. 2002. Effect of slope, grazing, and aeration on pasture hydrology. ASAE Paper No. 022156. St. Joseph, Mich.: ASAE.

Hansen, J. S., and J. E. Ongerth. 1991. Effects of time and watershed characteristics on the concentration of *Cryptosporidium* oocysts in river water. *Applied Environ. Microbiol*. 57(10): 2790-2795.

Health Canada. 2000. Waterborne outbreak of gastroenteritis associated with a contaminated municipal water supply, Walkerton, Ontario, May-June 2000. *Canada Communicable Disease Report* 26(20): 170-173.

Hoxie, N. J., J. P. Davis, J. M. Vergeront, R. D. Nashold, and K. A. Blair. 1997. Cryptosporidiosis-associated mortality following a massive waterborne outbreak in Milwaukee, Wisconsin. *American J. Public Health* 87(12): 2032-2035.

Hunt, P. G., R. E. Peters, T. C. Sturgis, and C. R. Lee. 1979. Reliability problems with indicator organisms for monitoring overland flow treated wastewater effluent. *J. Environ. Qual.* 8(3): 301-304.

Johnson, J. Y. M., J. E. Thomas, T. A. Graham, I. Townsend, J. Byrne, L. B. Selinger, and V. P. J. Gannon. 2003. Prevalence of *Escherichia coli* O157:H7 and *Salmonella* spp. in surface waters of southern Alberta and its relation to manure sources. *Canadian J. Microbiol*. 49(5): 326-335.

Kao, T. Y., and B. J. Barfield. 1978. Prediction of flow hydraulics for vegetated channels. *Trans. ASAE* 21(3): 489-494.

Kress, M., and G. R. Gifford. 1984. Fecal coliform release from cattle fecal deposits. *Water Resources Bulletin* 20(1): 61-66.

Li, R. M., and H. W. Shen. 1973. Effect of total vegetation on flow and sediment. *J. Hydrology, Proc. ASCE* 99(HY5): 793-814.

Lim, T. T., D. R. Edwards, S. R. Workman, and B. T. Larson. 1997. Vegetated filter strip length effects on quality of runoff from grazed pastures. ASAE Paper No. 972060. St. Joseph, Mich.: ASAE.

Moore, J. A., M. E. Grismer, S. R. Crane, and J. R. Miner. 1983. Modeling dairy waste management systems' influence on coliform concentration in runoff. *Trans. ASAE* 26(4): 1194-1200.

Moore, J. A., J. D. Smyth, E. S. Baker, and J. R. Miner. 1988. Evaluating coliform concentrations in runoff from various animal waste management systems. Special report 817. Corvallis, Ore.: Oregon State University, Agricultural Experiment Stations.

NRCS. 1997. NRCS conservation practice standard: Filter strip. Code 393. Lexington, Ky.: USDA Natural Resources Conservation Service.

Ong, C., W. Moorehead, A. Ross, and J. Isaac-Renton. 1996. Studies of *Giardia* spp. and *Cryptosporidium* spp. in two adjacent watersheds. *Applied Environ. Microbiol*. 62(8): 2798-2805.

Schellinger, G. R., and J. C. Clausen. 1992. Vegetated filter treatment of dairy barnyard runoff in cold regions. *J. Environ. Qual.* 21(1): 40-45.

Shelton, D., Y. A. Pachepsky, A. M. Sadeghi, W. L. Stout, J. S. Karns, and W. J. Gburek. 2003. Release rates of manure-borne coliform bacteria from data on leaching through stony soil. *Vadose Zone J.* 2: 34-39.

Srivastava, P., D. R. Edwards, T. C. Daniel, P. A. Moore, and T. A. Costello. 1996. Performance of vegetative filter strips with varying pollutant sources and filter strip length. *Trans. ASAE* 39(6): 2231-2239.

USDA and USEPA. 1999. Unified national strategy for animal feeding operations. Washington, D.C.: USDA and USEPA.

USEPA. 1994. National water quality inventory: Report to Congress. Washington, D.C.: USEPA, Office of Water.

Walker, S. E., S. Mostaghimi, T. A. Dillaha, and F. E. Woeste. 1990. Modeling animal waste management practices: Impact on bacteria levels in runoff from agricultural lands. *Trans. ASAE* 33(3): 807-817.

Wilson, L. G. 1967. Sediment removal from flood water. *Trans. ASAE* 10(1): 35-37.

Young, R. A., T. Huntrods, and W. Anderson. 1980. Effectiveness of vegetated buffer strips in controlling pollution from feedlot runoff. *J. Environ. Qual.* 9(3): 483-487.